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Central Exclusive Production at the Tevatron

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Abstract

In CDF we have observed several exclusive processes: $\gamma\gamma \to e^+e^-$ and $\mu^+\mu^-$, $\gamma + I\!\!P \to J/\psi, \psi(2S)$ and $I\!\!P + I\!\!P \to \chi_c$. The cross sections agree with QED, HERA photoproduction data, and theoretical estimates of $gg \to \chi_c$ with another gluon exchanged to screen the color. This observation of exclusive χ_c, together with earlier observations of exclusive dijets and exclusive $\gamma\gamma$ candidates, support some theoretical predictions for $p + p \to p + SMH + p$ at the LHC. Exclusive dileptons offer the best means of precisely calibrating forward proton spectrometers.

1 Central Exclusive Production

Central exclusive production at the Tevatron is the process $p+\bar{p} \to p+X+\bar{p}$, where "+" means a rapidity gap Δy exceeding 3 units, and X is a simple system fully measured. Exchanges (t-channel) over such large gaps must be color singlets with spin J [or Regge intercept $\alpha(0)] \geq 1.0$. Only photons γ or pomerons $I\!\!P$ qualify, apart from W and Z bosons which always cause the proton to break up. The gluon g would qualify apart from its color, but if another gluon is exchanged that can be cancelled, and $I\!\!P = gg$ is often a good approximation. It cannot be exact; QCD forbids a pure gg state, and a $q\bar{q}$ component certainly grows as Q^2 increases. The $I\!\!P$ has C = +1; in QCD one should also have a ggg state with C = -1, the odderon [1] O, not yet observed. The central masses M_X are roughly limited to $M_X <\approx \frac{\sqrt{s}}{20}$ with the outgoing protons at Feynman $x_F > 0.95$. Hence $M_X <\approx 3$ GeV at the CERN ISR [2], appropriate for glueball spectroscopy, where $M(\pi^+\pi^-)$ shows a broad $f_0(600)$, a narrow $f_0(980)$ and still unexplained structure possibly associated with $f_0(1710)$, a glueball candidate. The study of X = hadrons, e.g. $\phi\phi$ or $D^\circ\bar{D}^\circ$ to name two channels among many, has not been studied above ISR energies, but CDF is a perfect place to do it and hopefully we will.

At the LHC M_X can reach ≈ 700 GeV, into the electroweak sector, and we can have $X = Z, H, W^+W^-, ZZ$, slepton pairs $\tilde{l}\tilde{l}$, etc. Measuring the forward protons after 120m of 8T dipoles, in association with the central event, as the FP420 [3] proponents hope to do at ATLAS and CMS, one can measure M_X with $\sigma(M_X) \approx 2$ GeV per event [4], and for a state such as H, also its width if $\Gamma(H) >\approx 4$ GeV/c^2. There are scenarios (e.g. SUSY) in which FP420 could provide unique measurements. Two-photon collisions $\gamma\gamma \rightarrow l^+l^-, W^+W^-, \tilde{l}\tilde{l}$ become important at the LHC thanks to the intense high momentum photons, giving > 50 fb for W^+W^- as a continuum background to $H \rightarrow W^+W^-$.

While there is a gold mine of physics in $p+X+p$ at the LHC, we need to show that (a) the cross sections are within reach, and (b) one can build the spectrometers with resolution $\sigma(M_X) \approx 2$ GeV/c^2 and calibrate their momentum scale *and resolution*, to measure $\Gamma(H)$, and perhaps distinguish nearby states. Both these issues are addressed in CDF in a "TeV4LHC" spirit, and they are also very interesting in their own right. The calculation of cross sections (e.g. [5]) involves, in addition to $\sigma(gg \rightarrow X)$, the unintegrated gluon distribution $g(x_1, x_2)$, rapidity gap survival probability (no other parton interactions), and the Sudakov factor (probability of no gluon radiation producing hadrons). The Durham group predicts $\sigma(SMH)$ for $p+H+p$ at the LHC $= 3^{\times 3}_{\div 3}$ fb. At the Tevatron $p+H+\bar{p}$ is out of reach, but the process $p+\chi_c+\bar{p}$ is identical as far as QCD is concerned, as is $p+\gamma\gamma+\bar{p}$. Measuring these constrains the SMH cross section. In CDF we have looked for both exclusive $\gamma\gamma$ [6] and χ_c [7], without however having detectors able to see the p and $\bar{p}$. Instead we added forward calorimeters ($3.5 < |\eta| < 5.1$) and beam shower counters BSC ($5.5 < |\eta| < 7.4$). If these are all empty there is a high probability that both p and $\bar{p}$ escaped intact with small $|t|$. We also measured [8] exclusive dijets.

For the exclusive $\gamma\gamma$ search we triggered on events with two electromagnetic (EM) clusters with $E_T > 4$ GeV in the central calorimeter, with a veto on signals in the beam shower counters. This killed pile-up events and enabled us to take data without pre-scaling the trigger. We required all other detectors to be consistent with only noise; then our *effective* luminosity is only about 10% of the delivered luminosity. We found [6] 3 events with exactly two back-to-back EM-showers with $M(\gamma\gamma) > 10$ GeV/c^2. From chambers at the shower maximum we concluded that two were perfect $p+\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$ candidates and one was also consistent with being a $p+\bar{p} \rightarrow p+\pi^\circ\pi^\circ+\bar{p}$ event. The Durham prediction [9] was $0.8^{\times 3}_{\div 3}$ events, perfectly consistent. We have since accumulated more data, with a lower threshold, now being analysed.

With the above trigger we also found [10] 16 $p+\bar{p} \rightarrow p+e^+e^-+\bar{p}$ events, with $M(e^+e^-) > 10$ GeV/c^2 (up to 38 GeV/c^2), the QED $\gamma\gamma \rightarrow e^+e^-$ process. Exclusive 2-photon processes have not previously been observed in hadron-hadron collisions; the cross section agrees with the precise theory prediction. This process has been suggested as a means of calibrating the LHC luminosity; then it must be done in the presence of pile-up, and one will need to know the acceptance etc. at the few % level. More interesting for FP420 is that measurement of an exclusive lepton pair gives both forward proton momenta, with a precision dominated by the incoming beam momentum spread ($\frac{\delta p}{p} \approx 10^{-4}$, or 700 MeV). One can do this with pile-up, selecting dileptons with no associated tracks on the l^+l^- vertex and $\Delta\phi \approx \pi$. One can also cut on $p_T(l^+l^-)$ (correlated with $\Delta\phi$), but $\Delta\phi$ has better resolution. In CDF we found that a cut $\pi - \Delta\phi < \frac{0.6GeV}{M(l^+l^-)}$ is suitable for QED. For each pair one can predict ξ_1 and ξ_2, and, if a proton is in the FP420 acceptance, compare ξ_i and ξ_{420}. This also maps the acceptance A($\xi, t \approx$0), as the cross section shape is known from QED, and the (Coulomb) protons have very small t.

CDF also used a "muon+track" trigger, again with BSC veto, to study $p+\bar{p} \rightarrow p+\mu^+\mu^-+\bar{p}$ with 3 GeV/c^2 $< M(\mu\mu) <$4 GeV/c^2. This is a very rich region, with the J/ψ and $\psi(2S)$ vector mesons that can only be produced exclusively by photoproduction $\gamma + I\!\!P \rightarrow \psi$, or possibly by odderon exchange: $O + I\!\!P \rightarrow \psi$. We know what to expect for photoproduction from HERA, so an excess would be evidence for the elusive O.

The spectrum [7] is shown in Fig. 1, together with the sum of three components: the vector mesons and a continuum, $\gamma\gamma \to \mu^+\mu^-$, which is again consistent with QED. These central exclusive spectra are exceptionally clean; in fact the biggest background ($\approx$ 10%) is the identical process but with an undetected $p \to p^*$ dissociation. The J/ψ and $\psi(2S)$ cross sections $\frac{d\sigma}{dy}|_{y=0}$, are (3.92±0.62)nb and (0.54±0.15)nb, agreeing with expectations [11]. Thus we do not have evidence for O exchange, and put a limit $\frac{O}{\gamma} < 0.34$ (95% c.l.), compared with a theory prediction [12] 0.3 - 0.6.

While the QED and photoproduction processes in Fig. 1 should hold no surprises, their agreement with expectations validates the analysis. We required no EM tower with $E_T^{EM} > 80$ MeV. If we allow such signals (essentially γ's) the number of J/ψ events jumps from 286 to 352, while the number of $\psi(2S)$ only increases from 39 to 40. These extra J/ψ events are very consistent with being $\chi_{c0}(3415) \to J/\psi + \gamma$, from $I\!P I\!P \to \chi_c$, with about 20% of the γ being not detected (giving a background of 4% under the exclusive J/ψ). We measure $\frac{d\sigma}{dy}(\chi_c)|_{y=0} = (75\pm14)$nb. The existence of this process implies that $p + H + p$ must happen at the LHC (assuming H exists), and the χ_c cross section agrees with predictions: 150nb [13] and $130^{\times 4}_{\div 4}$nb [5]. It is therefore likely that $\sigma(p + p \to p + SMH + p)$ is of order 0.5-5 fb, within reach of FP420. In SUSY models the cross section can be much higher [3].

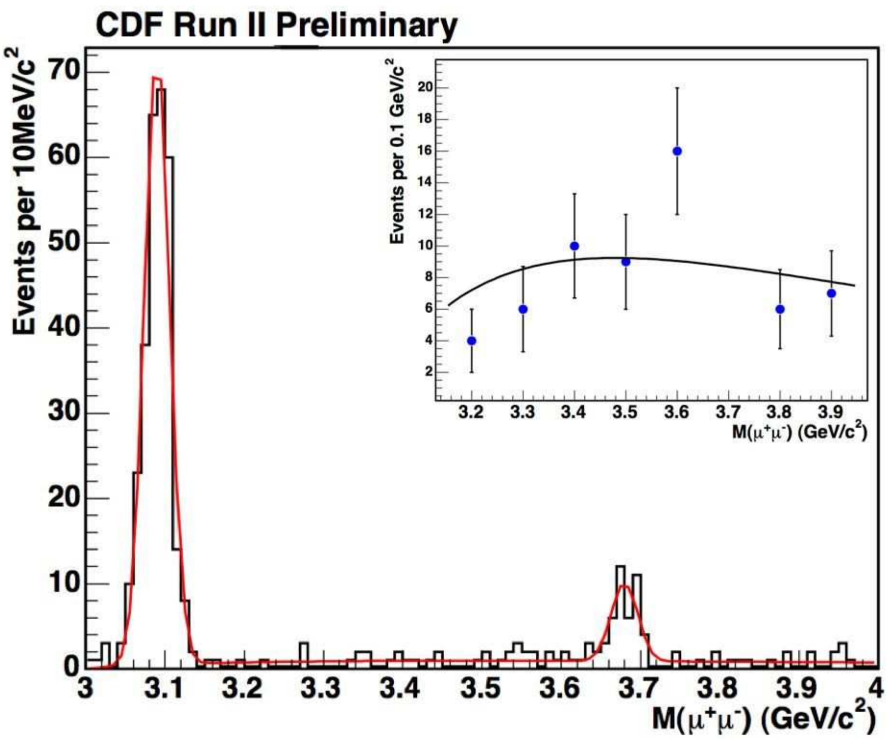

Figure 1: Exclusive dimuon mass spectrum in the charmonium region, together with the sum of two Gaussians and the QED continuum, shown in the inset, excluding the 3.65 - 3.75 GeV/c^2 bin ($\psi(2S)$). All line shapes are predetermined, with the normalization free.

We are looking for $p + \bar{p} \rightarrow p + \Upsilon + \bar{p}$ and $I\!P + I\!P \rightarrow \chi_b$. The Υ should be measurable in the presence of pile-up using $n_{ass} = 0$, $\Delta\phi$ and p_T cuts. The $\chi_b \rightarrow \Upsilon + \gamma$ probably can not, and is challenging. We have also made a search [14] for exclusive Z, allowed only through photoproduction $\gamma + I\!P \rightarrow Z$. In the Standard Model the (integrated) cross section at the Tevatron is too small to see, 0.3fb [15] or 1.3fb [16], before branching fractions. In White's pomeron theory [17] the cross section is expected to be much larger, but a quantitative prediction is lacking. Our search uses both e^+e^- and $\mu^+\mu^-$ pairs with $M(l^+l^-) > 40$ GeV/c^2. There are 8 exclusive candidates with $\sigma(p + \bar{p} \rightarrow p + (\gamma\gamma \rightarrow l^+l^-) + \bar{p} = 0.24^{+0.13}_{-0.10}$ pb, agreeing with $\sigma(\text{QED}) = 0.256$ pb. All the events have $\pi - \Delta\phi < 0.013$(rad) and $p_T(\mu^+\mu^-) < 1.2$ GeV/c. Only one event had a $\bar{p}$ in the acceptance of the Roman pots when they were operational, and a track was observed, showing that the event was exclusive, and that at the LHC such $l^+l^- + p$ events will be available for calibration. If we remove the requirement that the BSC should be empty there are 4 additional events, interpreted as $p \rightarrow p^*$ dissocation. One of them has $M(\mu^+\mu^-) \approx M(Z)$ and a larger $\Delta\phi$ and p_T than the others, but we cannot claim it to be truly exclusive. We put a limit on $\sigma(pp \rightarrow p + Z + \bar{p}) < 0.25$ pb at 95% c.l. Clearly it will be interesting to look for exclusive $p + Z + p$ at the LHC. In early running of the LHC, when bunch crossings without pile-up are not yet rare, it is important to measure these exclusive processes, to the extent possible without complete forward coverage. In CMS we have plans to add forward shower counters around the beam pipe to help tag rapidity gaps, along with the ZDC and forward hadron calorimeters. With large forward gaps in both directions, a trigger on two EM showers with $E_T >$ 4 GeV might be possible, hopefully observing $\Upsilon \rightarrow e^+e^-, \gamma\gamma \rightarrow e^+e^-$, $I\!P I\!P \rightarrow \gamma\gamma$, and $\chi_b \rightarrow \Upsilon$. Clean single interactions are surely needed needed for the χ_b and $I\!P I\!P \rightarrow \gamma\gamma$; both channels being excellent tests of $p + H + p$. One may even hope that when exclusive Higgs production is measured, the coupling ggH can be derived by comparing the three cross sections!

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